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Title: Nuclear Cloud Lofting

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Issued: 2016-04-13

Tumbler-Snapper Charlie
Nevada Test Site
31 kT

# ISR-1 Seminar
# Nuclear Cloud Lofting

Greenhouse George
Pacific Proving Grounds
225 kT

April 19th, 2016

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# Outline

- Motivation
- Background
- Lofting Methodologies
  - Empirical
  - Parcel Methods
  - Navier-Stokes
- DELFIC Model
- Validation
- DIORAMA Integration
- Conclusions

Tumbler-Snapper Dog
Nevada Test Site
19 kT

Total video duration: ~55 sec

Ground Zero Height: ~4,200 ft MSL
Initial Burst Height: ~5,200 ft MSL
Cloud Height at end of video: ~15,000 ft MSL

Final stabilized cloud properties (not shown in animation):

Cloud Top Height: 44,000 ft MSL

Cloud Bottom Height: 28,000 ft MSL

# Motivation

- **SNDD**
  - Space-based Nuclear Detonation Detection
  - Space-based instruments monitor a variety of phenomenologies for evidence of nuclear detonations
- Measurable phenomenologies vary with altitude

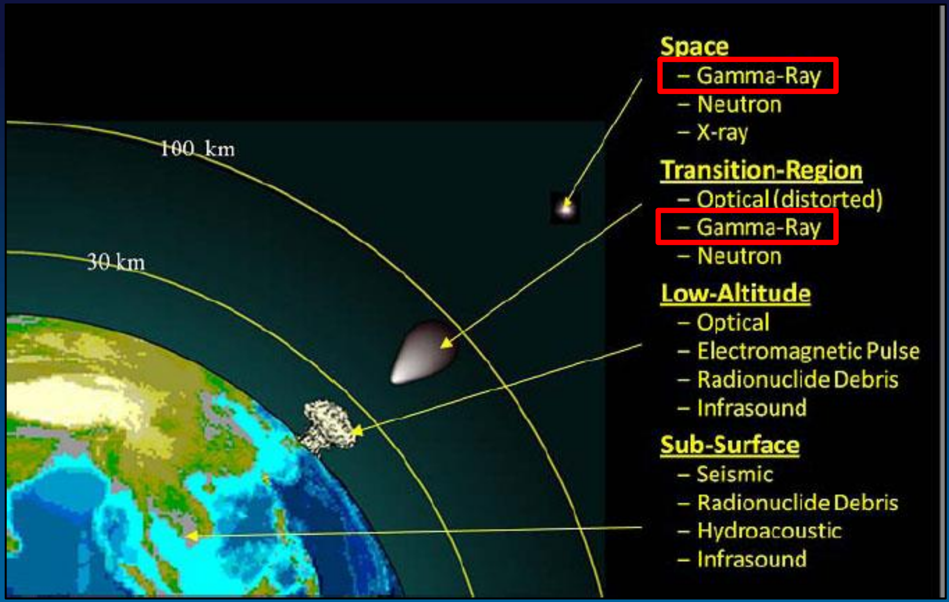



*Figure courtesy of U.S. DOE (2004)*

- For cloud lofting, we are interested in delayed gamma rays
  - Detected in space and transition region
  - Absorbed at low altitudes

# Motivation – Delayed Gamma Rays

- **Emission**
  - The gradual radioactive decay of fission products creates delayed gamma rays
  - The emission location of these delayed gamma rays follows the rise of the nuclear cloud

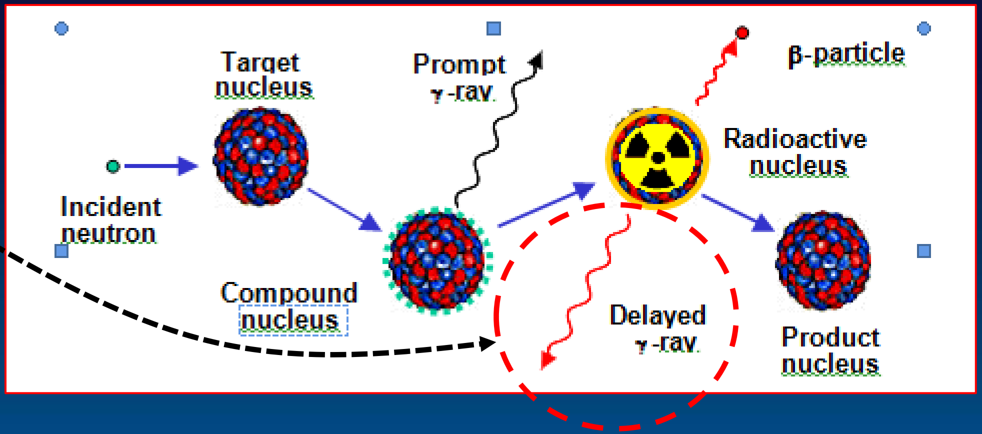
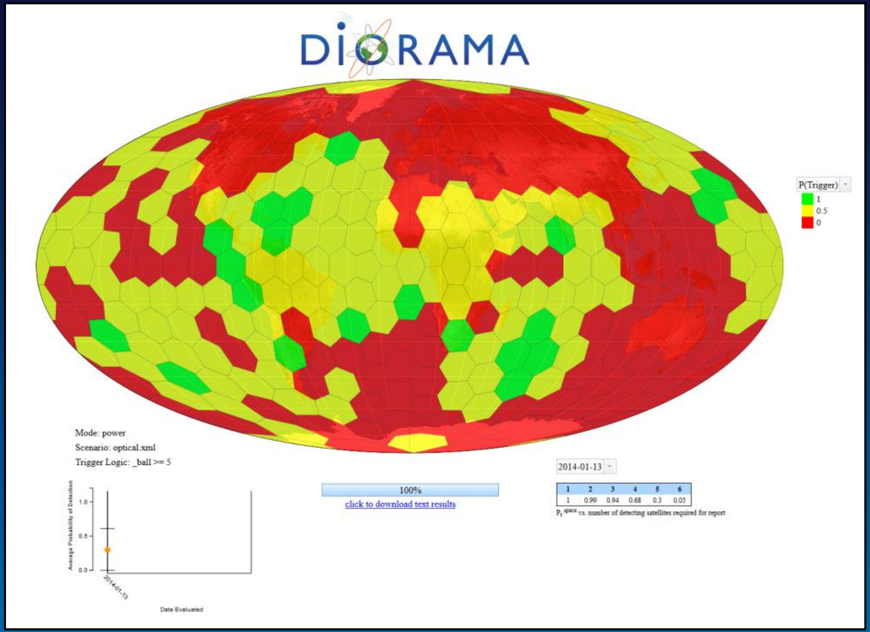



Figure from *The Effects of Nuclear Weapons* by Glasstone (1977)

- **Absorption**
  - At low altitudes, delayed gamma rays are absorbed by the atmosphere
  - At high altitudes, they may reach space-based instruments
- Lofting may bring the modeled radioactive cloud to an altitude where delayed gamma rays are detected by SNDD instruments

# Motivation

- **DIORAMA**
  - Distributed Infrastructure Offering Real-time Access for Modeling and Analysis
  - A framework that supports USNDS simulations from source to ground processing
  - Designed to replace the disparate array of specialized USNDS tools
- ***Goal**: To incorporate cloud lofting model into DIORAMA to <u>increase simulated detection of delayed gamma rays</u>*




*DIORAMA coverage simulation using only the optical phenemonology. Coverage uses a constellation of GPS satellites with look angle respondents (LARs).*

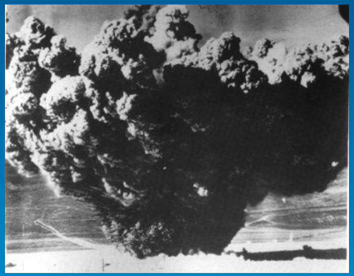
# Background – Burst Types

- Nuclear detonations can be divided into 5 "burst" categories
  - Underground
  - Underwater
  - Surface (< ~5000 ft above surface)
  - Air (> ~5,000 ft and < ~100,000 ft)
  - High-Altitude (> ~100,000 ft)
- For cloud lofting, only the latter three are considered.

**UNDERGROUND**
Plumbbob Rainier
Nevada Test Site
1.7 kT

**UNDERWATER**
Crossroads Baker
Pacific Proving Grounds
23 kT

**SURFACE**
Buster-Jangle Sugar
Nevada Test Site
1.2 kT



**AIR**
Upshot-Knothole Dixie
Nevada Test Site
11 kT

**HIGH ALTITUDE**
Fishbowl Starfish Prime
Pacific Proving Grounds
1.4 MT

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# Background – Lofting Basics

- Nuclear Cloud Lofting is the rise and growth of a cloud (resulting from a nuclear detonation) through the atmosphere
- At low altitudes (<50 km), the rise of the cloud is dominated by the buoyant force
- At higher altitudes, the ballistic force becomes important

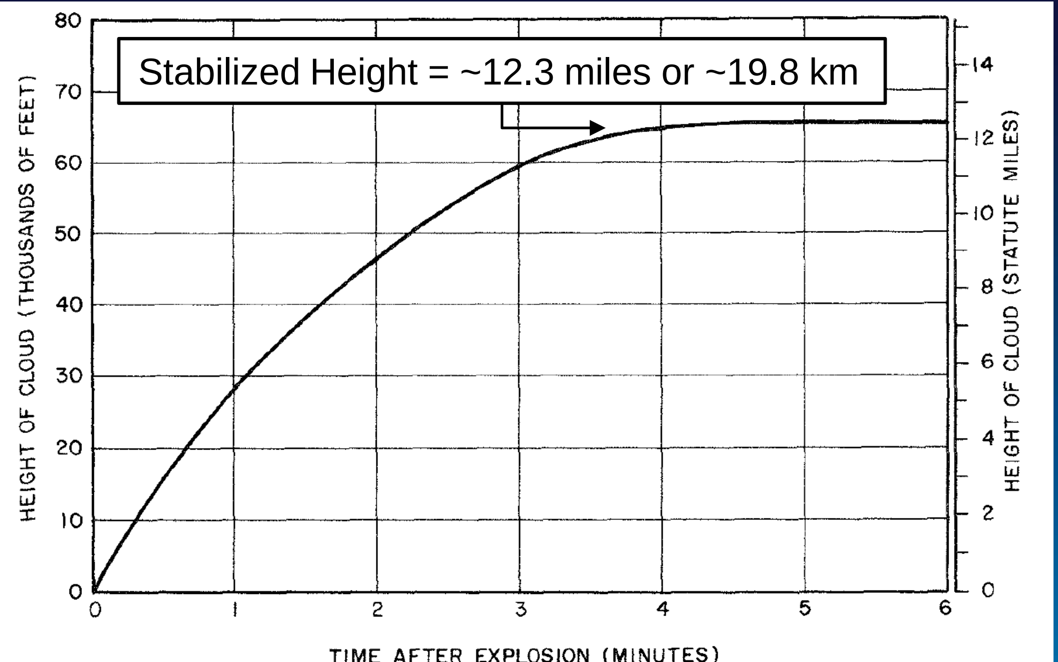


Figure 2.12. Height of cloud top above burst height at various times after a 1-megaton explosion for a moderately low air burst.

Figure from *The Effects of Nuclear Weapons* by Glasstone (1977)

# Background – Pressure Equilibrium

Los Alamos NATIONAL LABORATORY EST.1943

- The physics in the first few seconds after a nuclear detonation are extremely complex
- However, within a matter of seconds, the nuclear cloud has come into **pressure equilibrium** with the surrounding atmosphere and cooled from millions of Kelvin to several thousand Kelvin
- Pressure equilibrium simply states: $P_c = P_a$
- This can be rewritten with the ideal gas law: $P = \rho k_B T$
- $\rho_c k_B T_c = \rho_a k_B T_a \Rightarrow \rho_c = \rho_a \frac{T_a}{T_c} \Rightarrow \rho_c \ll \rho_a$

$\rho_c$ = Cloud density
$T_c$ = Cloud temperature
$P_c$ = Cloud Pressure

$\rho_a$ = Atmospheric density
$T_a$ = Atmospheric temperature
$P_a$ = Atmospheric Pressure

$k_B$ = Boltzmann constant

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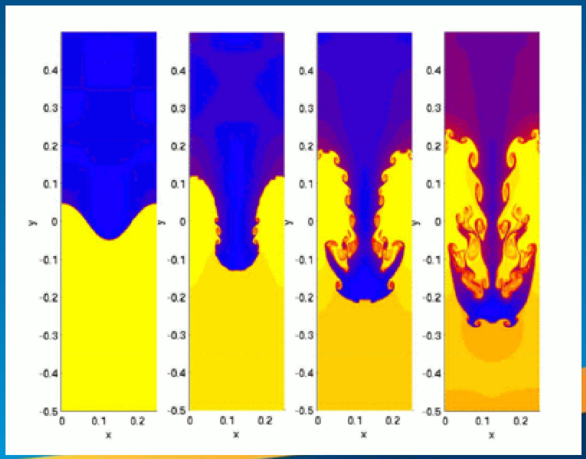
# Background – Buoyancy

- The strong buoyant force is the result of the high temperature of the cloud (and hence low density due to pressure equilibrium) that causes it rise much like a hot air balloon
- The buoyant force is defined as $F_B = V_c(\rho_a - \rho_c)g$
- For a ~50 kT detonation, the cloud temperature when pressure equilibrium is achieved is ~3000 K compared to the atmospheric temperature of ~300 K (assuming a surface burst)
- For this case, the nuclear cloud is therefore ~10x less dense than the surrounding atmosphere

$V_c$ = Cloud Volume  $\rho_c$ = Cloud density  $\rho_a$ = atmospheric density  $g$ = gravitational acceleration

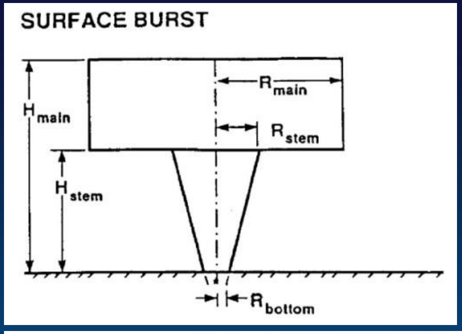
# Background – Toroidal Vortex

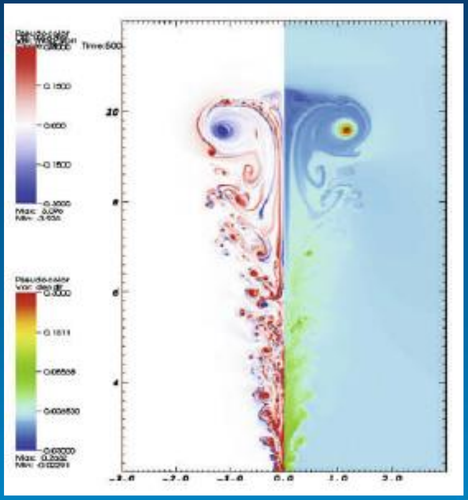
- A Rayleigh-Taylor instability forms due to the different densities of the cloud and atmosphere
  - (Upper Right) The Rayleigh-Taylor instability in the nuclear cloud
  - (Lower Right) A Rayleigh-Taylor instability for a heavier fluid above a lighter (immisicible) fluid
- This manifests in a toroidal vortex that entrains atmospheric gas and causes the cloud to rapidly grow in radius and mass
- The entrainment of cooler atmospheric gas causes the average cloud temperature and density to approach atmospheric equilibrium
- The cloud stabilizes when equilibrium is achieved and the buoyant force is zero



# Lofting Methodologies

- There are three primary methodologies that can be applied to the problem of Cloud Lofting:
  - Empirical
  - Parcel
  - Navier-Stokes
- A <u>parcel</u> methodology was chosen for this work as a tradeoff between speed and accuracy



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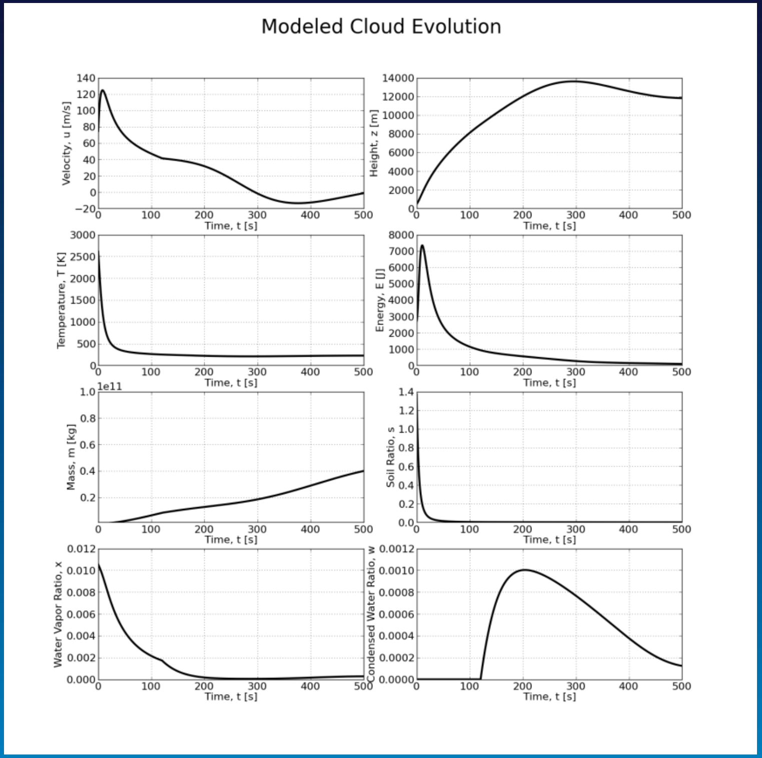
# Empirical Models

- Ignores the physics and uses fitting equations to best fit the data
- Previous empirical models
  - Newgarden and Spohn (1955) (LASL)
  - Brode (1968)
  - Harvey (1992)
  - NATO (2014)
- Pros
  - Least computational effort
  - Comparable accuracy to parcel methods for stabilized cloud height
- Cons
  - Limited range of applicability (only certain yields, altitudes, etc.)
  - Neglect atmospheric properties
  - Only deal with stabilized cloud height and ignore evolution

# Parcel Methods

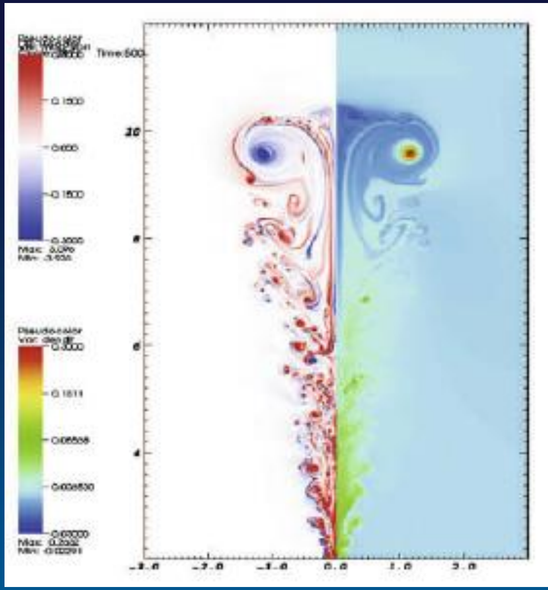
- Simplified physics equations that treat cloud as a single homogeneous unit
- Previous parcel methods
  - Taylor (1945)
  - Machta (1950)
  - Huebsch (1964) - DELFIC Model
  - Onufriev (1970)
- Pros
  - Extended range of validity (higher altitudes, atmospheric effects)
  - Includes temporal evolution of cloud
- Tradeoffs
  - Moderate error (~10% error in height over range of weapon yields and altitudes)
  - Moderate computational effort (~1 – 2 seconds per simulation)

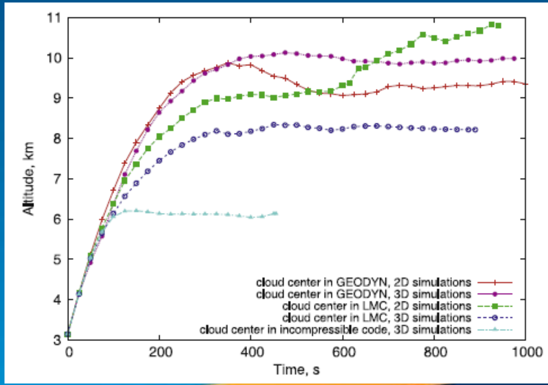



*Sample DELFIC Model Output – Time history of 8 cloud properties until stabilization*

# Navier-Stokes Methods

- Non-linear partial differential set of equations for continuum fluids
- Previous Navier-Stokes methods
  - Krispin (2000)
  - Kanarska (2009)
- Pros
  - Most accurate (~5% error in cloud height compared to observations)
  - Accurate throughout continuum region (< 200 km)
  - Full evolution of the cloud
- Cons
  - Multi-year, multi-person efforts to program
  - Computationally expensive (~Hours of computation)



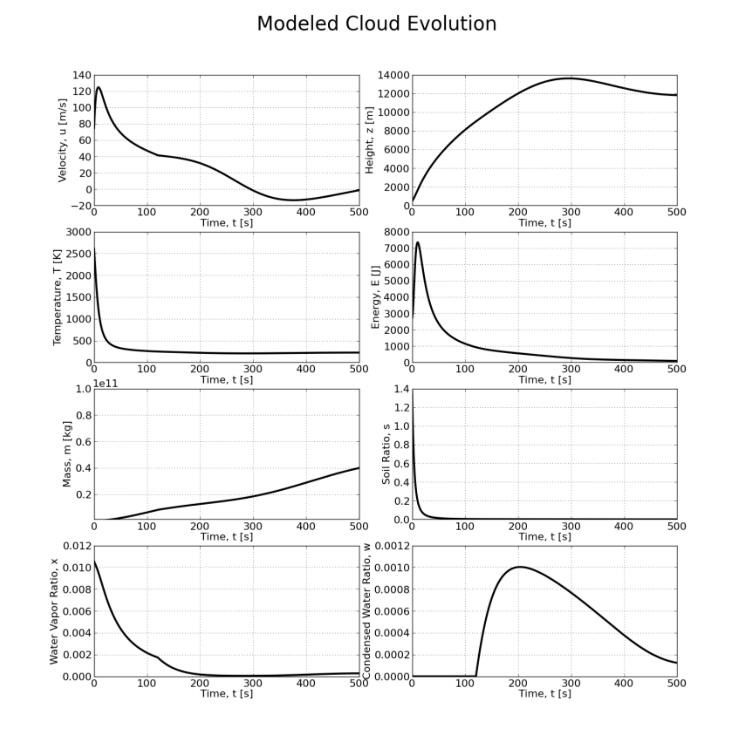


# DIORAMA requirements

- DIORAMA requires cloud lofting computed < *10 seconds*
  - This constraint eliminates the **Navier-Stokes equations**
- DIORAMA requires the time history of the cloud height
  - This constraint eliminates the **empirical models**
- Only the parcel methodologies remain
- The DELFIC parcel method was chosen because:
  - DELFIC = *Defense Land Fallout Interpretive Code*
  - Simulations only require ~5 seconds on a single core
  - The time history of the cloud is given
  - Atmospheric properties are taken into account (e.g. density, temperature, humidity)

# DELFIC Model - Fundamentals

- DELFIC solves a set of 8 coupled ordinary differential equations
- The 8 independent variables are:
  - Temperature, $T$
  - Mass, $m$
  - Height, $z$
  - Velocity, $v$
  - Energy, $E$
  - Soil ratio, $s$
  - Water Vapor Ratio, $x$
  - Condensed Water Ratio, $w$




*Sample DELFIC Model Output – Time history of 8 cloud properties until stabilization*

# Model – Initial Conditions (P1)

- To solve the set of ODEs, initial conditions are required
- The physics of the fireball prior to pressure equilibrium are ignored and semi-empirical relations fit to observational data are used for the initial conditions
- Temperature - $T_{ci} = K\left(\frac{t_i}{t_{2m}}\right)^n + 1500$
  - K and n are yield dependent empirical parameters:
    - $K = 6847W^{-0.0131}$
    - $n = -0.4473W^{0.0436}$
  - $t_i$ - Time of pressure equilibrium (seconds) - $t_i = 56t_{2m}W^{-0.30}$
  - $t_{2m}$ - Time of the 2$^{nd}$ temperature maximum - $t_{2m} = 0.045W^{0.42}$

# Model – Initial Conditions (P2)

- The initial mass of the cloud is split between air, water vapor, and soil.
  - The cloud is assumed to be so hot that no condensed water vapor can exist
- The energy that heats the cloud, $H$, is assumed to be 45% of the total yield
  - This factor is the result of extensive simulations with the original DELFIC code
  - A factor $\varphi$ defines the fraction of energy that heats water for a blast over water
- Soil Mass, $m_{si} = k_{\Lambda} W^{3/3.4}(180 - \lambda)^2(360 + \lambda)$
  - $\lambda$ is the scaled height of burst and $k_{\Lambda}$ = 0.07741 kg ft$^3$
  - For pure airbursts, $m_{si}$ is set to a constant weapon mass
- Air Mass, $m_{ai} = \dfrac{\varphi\left[H - m_{si}\int_{T_{ei}}^{T_{si}} c_s(T)dT\right]}{\int_{T_{ei}}^{T_{ci}} c_{pa}(T)dT + x_e\int_{T_{ei}}^{T_{ci}} c_{pw}(T)dT}$
  - $c_s(T)$, $c_{pa}(T)$, and $c_{pw}(T)$ are the specific heats of soil, air, and water (constant pressure)
  - $T_{si}$, $T_{ei}$, and $T_{ci}$ are the initial temperatures of soil, the atmosphere, and cloud [K]
  - $x_e$ is the atmospheric ratio of water vapor

# Model – Initial Conditions (P3)

- Initial Water Vapor Mass, $m_{xi} = \frac{(1-\varphi)\left[H - m_{si}\int_{T_{ei}}^{T_{si}} c_s(T)\,dT\right]}{\int_{T_{ei}}^{T_{ci}} c_{pw}(T)\,dT + L} + x_e m_{ai}$
- Initial Condensed Water Mass, $m_{wi} = 0$
- Species Ratios
  - Soil Ratio, $s_i = \frac{m_{si}}{m_{ai}}$
  - Water Vapor Ratio, $x_i = \frac{m_{xi}}{m_{ai}}$
  - Condensed Water Ratio, $w_i = \frac{m_{wi}}{m_{ai}}$
- Height, $z_i = z_{GZ} + z_{HOB} + 90W^{1/3}$
- Velocity, $u_i = 1.2\sqrt{gR_{ci}}$
- Energy Density, $E_i = \frac{1}{2}u_i^2$

$z_i$ = Initial cloud center height [m]
$z_{GZ}$ = Height of ground zero [m]
$z_{HOB}$ = Height of burst above GZ [m]

$u_i$ = Initial cloud center velocity [m/s]
$E_i$ = Initial cloud energy density [J/kg]
$R_{ci}$= Initial horizontal cloud radius [m]

$L$ = Latent heat of condensation
$g$ = Gravitational acceleration [m/s$^2$]
$W$= Yield [kT]

# Model – Wet & Dry Equations

- Due to the importance of condensation in the cloud, the model switches between two sets of equations “wet” and “dry”
  - The wet equations include the effect of the latent heat of condensation of water when liquid water is present
  - Latent heat is ignored in the dry equations since there is no condensed water
- Switch between “wet” and “dry” equations controlled by $P_v$
  - $P_v$ = partial pressure of water vapor in the cloud [Pa]
  - $P_{ws}$ = saturation water vapor pressure [Pa]
  - If $P_v > P_{ws}$, “wet” equations apply
  - If $P_v \le P_{ws}$, “dry” equations apply

# Model – Differential Equations

- The set of ODEs is solved using an 8th order accurate adaptive timestep scheme using the GNU Scientific Library (GSL)
- **Height**: $\frac{dz}{dt} = u$
- **Velocity**: $\frac{du}{dt} = \underbrace{\left(\frac{T_{vc}}{T_{ve}}\beta - 1\right)}_{a} g - \left(\underbrace{\frac{2k_2 v}{H_c}\frac{T_{vc}}{T_{ve}}\beta}_{b} + \underbrace{\frac{1}{m}\frac{dm}{dt}}_{c}\right) u$
  - Term 'a' accounts for the cloud buoyancy
  - Term 'b' accounts for eddy-viscous drag
  - Term 'c' accounts for entrainment drag

$z$ = Cloud center height [m]
$u$ = Cloud center velocity [m/s]
$t$ = Time from detonation [s]
$k_2$ = kinetic to turbulent energy conversion factor [unitless]
$T_{vc}$ = Virtual cloud temperature [K]
$T_{ve}$ = Virtual atmos. temperature [K]
$H_c$ = Vertical cloud radius [m]
$v$ = characteristic cloud velocity [m/s]
$\beta$ = Gas to total density ratio [unitless]
$g$ = Gravitational acceleration [m/s$^2$]

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# Model – Temperature Equations

- The temperature equation has both "wet" and "dry" forms
- **Dry equation**: $$\frac{dT_c}{dt} = \frac{-\beta}{\bar{c}_p(T_c)}\left[\overbrace{\frac{T_{vc}}{T_{ve}} gu}^{a} + \overbrace{\frac{1}{\beta m}\frac{dm}{dt}}^{b} \overbrace{- \zeta}^{c}\right]$$
  - Term 'a' accounts for adiabatic expansion
  - Term 'b' accounts for entrainment
  - Term 'c' accounts for turbulent dissipation of kinetic energy to heat
- **Wet equation**:

$$\frac{dT_c}{dt} = -\frac{\beta}{1+\frac{L^2 x\varepsilon}{c_p(T_c) R_a T_c^2}}\left[\overbrace{\left(T_c - T_e + \frac{L(x-x_e)}{c_p(T_c)}\right)\frac{1}{m\beta}\frac{dm}{dt}}^{b} + \overbrace{\frac{T_{vc}}{T_{ve}}\frac{gu}{c_p(T_c)}\left(1 + \frac{Lx}{R_a T_c}\right)}^{a} \overbrace{- \frac{\zeta}{c_p(T_c)}}^{c}\right]$$

  - Terms are the same as for "dry" equation

# Model – Energy & Soil Equations

- **Energy**: $$\frac{dE}{dt} = \overbrace{\frac{2k_2\beta u^2 v}{H_c}\frac{T_{vc}}{T_{ve}}}^{a} + \overbrace{\frac{u^2}{2m}\frac{dm}{dt}}^{b} - \overbrace{\frac{E}{m}\frac{dm}{dt}}^{c} - \overbrace{\zeta}^{d}$$
  - Term 'a' accounts for turbulent energy generated by eddy viscous drag
  - Term 'b' accounts for turbulent energy generated by entrainment
  - Term 'c' accounts for entrainment dilution of energy
  - Term 'd' accounts for turbulent dissipation of kinetic energy to heat
- **Soil**: $$\frac{ds}{dt} = -\overbrace{\frac{1}{\beta}\left(\frac{1+x}{1+x_e}\right)\frac{s}{m}\frac{dm}{dt}}^{a}$$
  - Term 'a' accounts for entrainment dilution

# Model – Mass Equations

- The mass equation has both “wet” and “dry” forms

- **Dry equation**: $\frac{dm}{dt} = \frac{\overbrace{mS\mu v}^{a}}{V}$
  - Term ‘a’ accounts for entrainment
  - The mass lost to fallout is neglected as studies have shown it is negligible
  - $S$ = cloud surface area [m$^2$], $V$ = cloud volume [m$^3$], $\mu$ = entrainment factor

- **Wet equation**:

$$\frac{dm}{dt} = \frac{\beta m}{1 - \frac{1}{T_{vc}}\left(\frac{\beta}{1+\frac{L^2 x \varepsilon}{c_p(T_c) R_a T_c^2}}\right)\left[T_c - T_e + \frac{L(x-x_e)}{c_p(T_c)}\right]} \times \left\{\frac{S\mu v}{V} + \frac{1}{T_{vc}}\left(\frac{\beta}{1+\frac{L^2 x \varepsilon}{c_p(T_c) R_a T_c^2}}\right)\left[\frac{gu}{c_p(T_c)}\frac{T_{vc}}{T_{ve}}\left(1+\frac{Lx}{R_a T_c}\right) - \frac{\zeta}{c_p(T_c)}\right] - \frac{gu}{R_a T_{ve}}\right\}$$

  - The entire right-hand side accounts for entrainment modified for the condensation of water

# Model – Water Vapor Equations

- The water vapor equation has both "wet" and "dry" forms
- **Dry equation**: $\frac{dx}{dt} = -\overbrace{\frac{1+x+s}{1+x_e}(x - x_e)\frac{1}{m}}^{\text{a}}\frac{dm}{dt}$
  - Term 'a' accounts for entrainment
- **Wet equation**: $\frac{dx}{dt} = \left[\left(1 + \frac{x}{\varepsilon}\right)\frac{L\varepsilon}{R_a T_c^2}\frac{dT}{dt} + \left(1 + \frac{x}{\varepsilon}\right)\frac{gu}{R_a T_{ve}}\right]x$
  - Terms are the same as for the "dry" equation

# Model – Cond. Water Equations

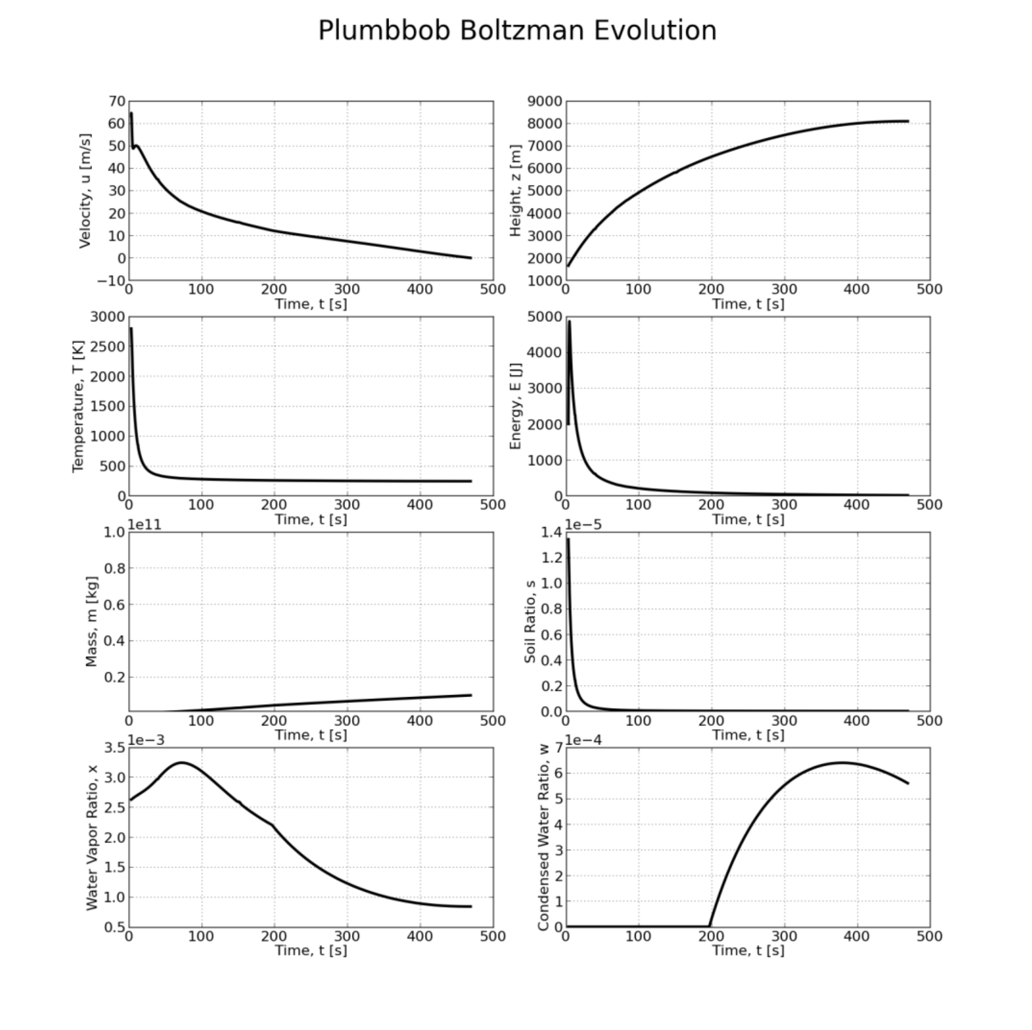
- The condensed water equation has both "wet" and "dry" forms
- **Dry equation**: $\frac{dw}{dt} = 0$
  - No condensed water exists under "dry" conditions
- **Wet equation**: $\frac{dw}{dt} = \overbrace{-\frac{1}{\beta}\left(\frac{1+x}{1+x_e}\right)(w + x - x_e)\frac{1}{m}\frac{dm}{dt}}^{a}\overbrace{-\frac{dx}{dt}}^{b}$
  - Term 'a' accounts for entrainment dilution
  - Term 'b' accounts for condensation of water vapor

# Model – Atmospheric Properties

- Nearly all of the ODEs are dependent on the atmospheric properties such as temperature, pressure, and humidity
- To compute atmospheric properties, NRLMSISE-00 is used
  - NRLMSISE-00 = Naval Research Laboratory Mass Spectrometer and Incoherent Scatter
  - MSIS does not include humidity
- Humidity data is taken from NCAR archived datasets
  - NCAR = National Center for Atmospheric Research
  - 16 datasets are interpolated for the simulation humidity
    - 4 seasonal datasets groups separated by 3 months
    - Each seasonal dataset group includes data from a single day with 4 datasets separated by 6 hours
    - Each dataset has the maximum NCAR vertical resolution (~10 kPa intervals)
    - 10 x 10 degree resolution for latitude and longitude

# Simulation Results

- Plumbbob Boltzman
  - 12 kT Yield
  - Nevada Test Site
  - 500 ft Height of Burst
- Cloud top height
  - Observed: 10058 m
  - Model: 9308 m
  - Percentage error: 7.2%
- Cloud bottom height
  - Observed: 7010 m
  - Model: 6819 m
  - Percentage error: 2.7%

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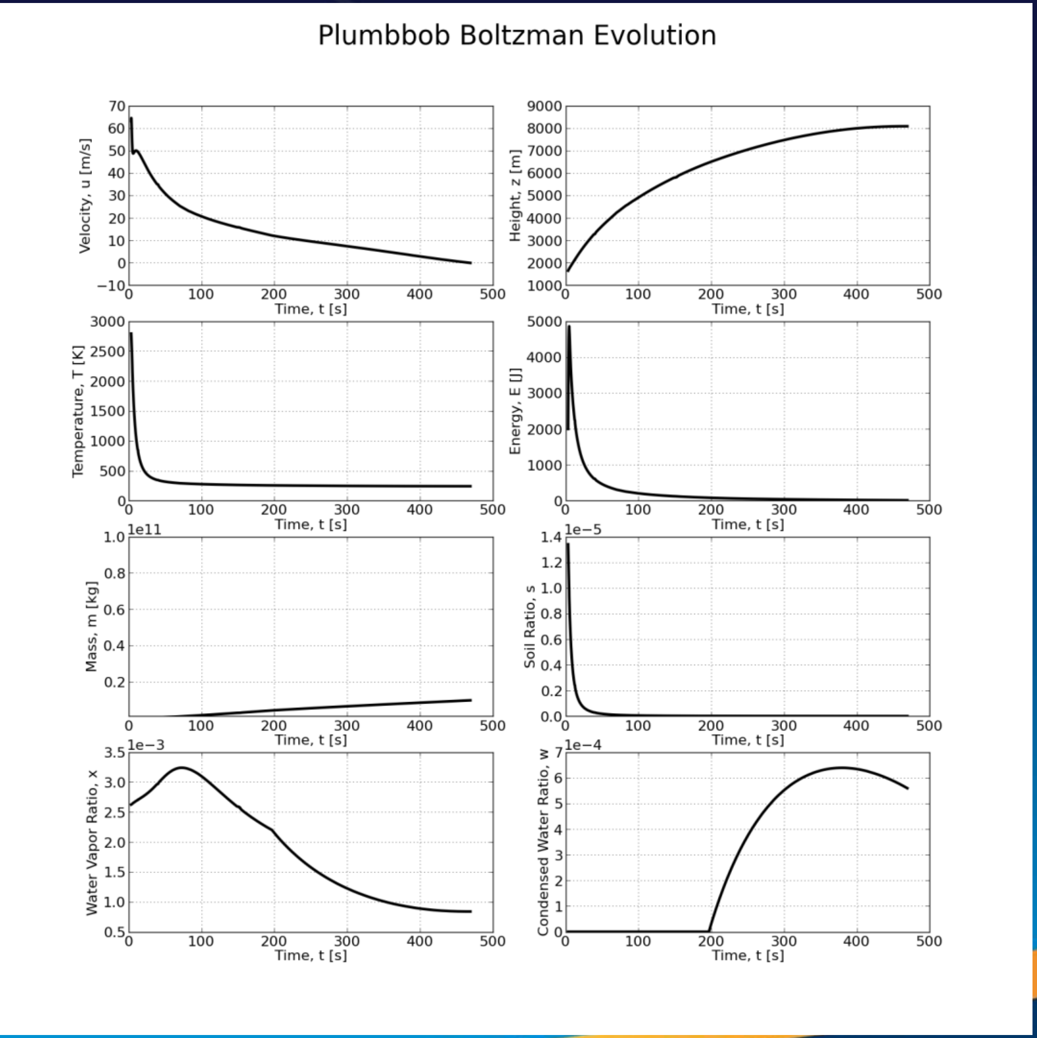
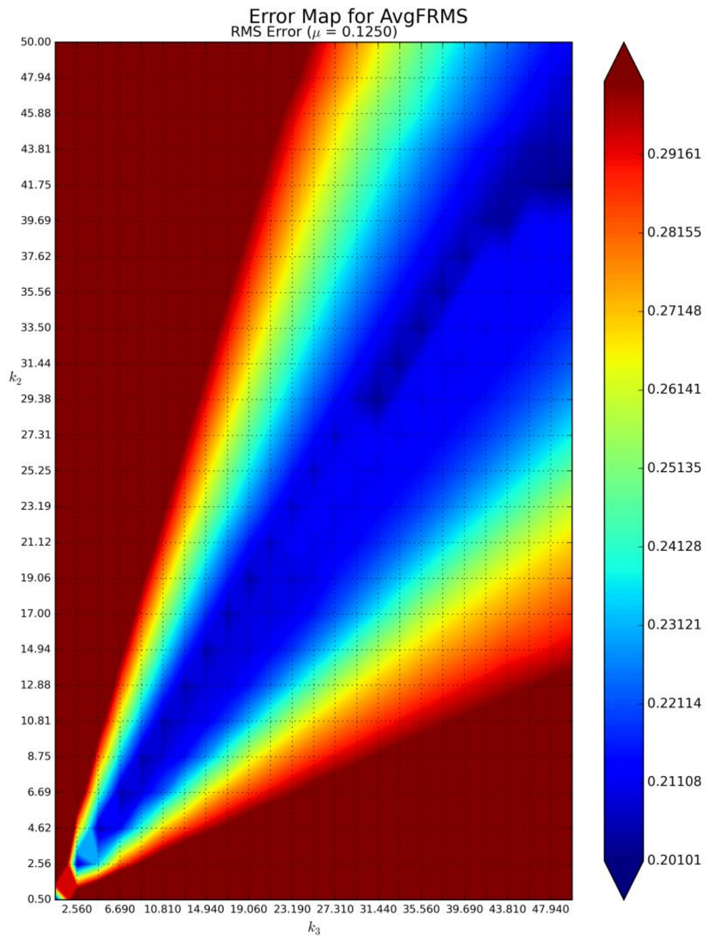
# Simulation Results

- Initial cloud properties
  - Initial velocity, ~60 m/s
  - Initial temperature, ~2800 K
  - Initial cloud height, ~700 m
- Evolution properties
  - Cloud height asymptotically approaches stabilization height
  - Temperature and energy rapidly decay due to entrainment and mixing with atmospheric gas
  - Mass increases nearly linearly
  - Soil ratio decays rapidly due to entrainment of atmospheric gas
  - Discontinuity in water vapor at ~200 s signals switch to “wet” equations



# Model Tuning & Validation

- The cloud lofting module includes three tunable parameters
  - $\mu$ = entrainment parameter
  - $k_2$ = eddy viscous drag parameter
  - $k_3$= turbulent dissipation rate pre-factor
- These parameters are necessary because the complex physics of the turbulent mixing between the cloud and atmospheric gas is not modeled in detail
- The parameters are tuned by a brute force iterative search over the global parameter space
- For each set of tuning parameters, 54 simulations corresponding to historical nuclear tests are run

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# Model Tuning & Validation

- For each simulation, the top, bottom, and average cloud height fractional deviation ($FD$) is computed using:
  - $FD = \frac{z_{obs} - z_{calc}}{z_{obs}}$
- To determine the error across all 54 tests for a specific set of parameters, the fractional root mean square (FRMS) is computed:
  - $FRMS = \sqrt{\frac{\sum_N (FD)^2}{N}}$
- Errors were also computed to previous DELFIC implementations (Jodoin, 1994)

| Test | Yield (kt) | Observed Cloud Top (m) | Model Top Height (m) | | Fractional Dev. | |
|---|---|---|---|---|---|---|
| | | | Jodoin | C++ | Jodoin | C++ |
| HardtackII Humboldt | 0.0078 | 2286 | 2274 | 2283 | 0.0054 | -0.0002 |
| HardtackII Catron | 0.021 | 2591 | 2656 | 2509 | -0.0253 | 0.0301 |
| HardtackII Vesta | 0.024 | 3048 | 3535 | 2961 | -0.1598 | 0.0268 |
| HardtackII DonaAna | 0.037 | 3353 | 4209 | 2897 | -0.2554 | 0.1347 |
| HardtackII Hidalgo | 0.077 | 3658 | 3906 | 3180 | -0.0679 | 0.1291 |
| HardtackII Quay | 0.079 | 3048 | 3094 | 3124 | -0.015 | -0.0269 |
| HardtackII Eddy | 0.083 | 3353 | 4063 | 3240 | -0.2119 | 0.0317 |
| HardtackII RioArriba | 0.09 | 4115 | 3803 | 3125 | 0.0757 | 0.2392 |
| HardtackII Wrangell | 0.115 | 3048 | 3256 | 3406 | -0.0683 | -0.1196 |
| Plumbbob Franklin | 0.14 | 5090 | 5498 | 3405 | -0.08 | 0.3297 |
| Plumbbob Wheeler | 0.197 | 5182 | 5126 | 3717 | 0.0108 | 0.281 |
| Upshot-Knothole Ray | 0.2 | 3901 | 3782 | 3658 | 0.0307 | 0.0603 |
| Upshot-Knothole Ruth | 0.2 | 4145 | 4363 | 3731 | -0.0525 | 0.098 |
| Sunbeam JonnieBoy | 0.5 | 5182 | 4388 | 5106 | 0.1531 | 0.0116 |
| Plumbbob Laplace | 1 | 6096 | 6323 | 5139 | -0.0373 | 0.1547 |
| HardtackII SantaFe | 1.3 | 5486 | 5987 | 5841 | -0.0913 | -0.0676 |
| HardtackII Lea | 1.4 | 5182 | 6269 | 5877 | -0.2099 | -0.1375 |
| Plumbbob John | 2 | 13411 | 11944 | 12371 | 0.1094 | 0.0762 |
| HardtackII Mora | 2 | 5639 | 6254 | 6290 | -0.1091 | -0.1188 |
| HardtackII DeBaca | 2.2 | 5334 | 6722 | 6439 | -0.2602 | -0.2104 |
| Plumbbob FranklinPrime | 4.7 | 9754 | 7345 | 7184 | 0.2469 | 0.2613 |
| HardtackII Sanford | 4.9 | 7925 | 7337 | 7188 | 0.0742 | 0.09 |
| HardtackII Socorro | 6 | 7925 | 8005 | 7863 | -0.0101 | 0.0053 |
| Plumbbob Morgan | 8 | 12192 | 8210 | 8016 | 0.3266 | 0.3405 |
| Plumbbob Owens | 9.7 | 10668 | 8844 | 8345 | 0.171 | 0.2154 |
| Plumbbob Kepler | 10 | 8534 | 9114 | 8437 | -0.0679 | 0.0082 |
| Plumbbob Wilson | 10 | 10668 | 9429 | 8722 | 0.1162 | 0.1771 |
| Upshot-Knothole Dixie | 11 | 13716 | 11743 | 10126 | 0.1438 | 0.26 |
| Plumbbob Doppler | 11 | 11582 | 9054 | 8963 | 0.2183 | 0.2237 |
| Plumbbob Fizeau | 11 | 12192 | 9296 | 8526 | 0.2376 | 0.2984 |
| Plumbbob Galileo | 11 | 11278 | 9477 | 8589 | 0.1597 | 0.2355 |
| Plumbbob Boltzman | 12 | 10058 | 11330 | 9308 | -0.1264 | 0.0719 |
| Plumbbob Charleston | 12 | 9754 | 8543 | 9111 | 0.1241 | 0.063 |
| Plumbbob Newton | 12 | 9754 | 9790 | 9109 | -0.0037 | 0.0631 |
| Plumbbob Grable | 15 | 10668 | 7523 | 9167 | 0.2948 | 0.1377 |
| Upshot-Knothole Annie | 16 | 12497 | 11358 | 8746 | 0.0912 | 0.265 |
| Plumbbob Diablo | 17 | 9754 | 10686 | 9783 | -0.0956 | -0.0089 |
| Plumbbob Shasta | 17 | 9754 | 10207 | 9534 | -0.0464 | 0.0191 |
| Plumbbob Stokes | 19 | 11278 | 10465 | 9101 | 0.072 | 0.1014 |
| Plumbbob Whitney | 19 | 9144 | 10562 | 9775 | -0.1551 | -0.0727 |
| Upshot-Knothole Badger | 23 | 10973 | 10357 | 10200 | 0.0561 | 0.0676 |
| Upshot-Knothole Nancy | 24 | 12650 | 10622 | 9470 | 0.1603 | 0.2018 |
| Upshot-Knothole Encore | 27 | 12802 | 10922 | 10846 | 0.1468 | 0.1495 |
| Upshot-Knothole Harry | 32 | 12954 | 13952 | 11316 | -0.0771 | 0.1237 |
| Plumbbob Priscilla | 37 | 13106 | 12301 | 11513 | 0.0615 | 0.118 |
| Redwing Lacrosse | 40 | 11582 | 8988 | 10137 | 0.224 | 0.1138 |
| Upshot-Knothole Simon | 43 | 13411 | 13564 | 11053 | -0.0114 | 0.1252 |
| Plumbbob Smoky | 44 | 11582 | 12760 | 11857 | -0.1016 | 0.0484 |
| Upshot-Knothole Climax | 61 | 13015 | 13686 | 12495 | -0.0516 | 0.038 |
| Plumbbob Hood | 74 | 14630 | 14687 | 13757 | -0.0039 | 0.0574 |
| Castle Koon | 110 | 16154 | 14999 | 16980 | 0.0715 | -0.052 |
| Redwing Zuni | 3500 | 24079 | 27285 | 31526 | -0.1331 | -0.271 |
| Redwing Tewa | 5000 | 30175 | 29525 | 29502 | 0.0216 | 0.0178 |
| Castle Bravo | 15000 | 34747 | 36120 | 47117 | -0.0395 | -0.1169 |

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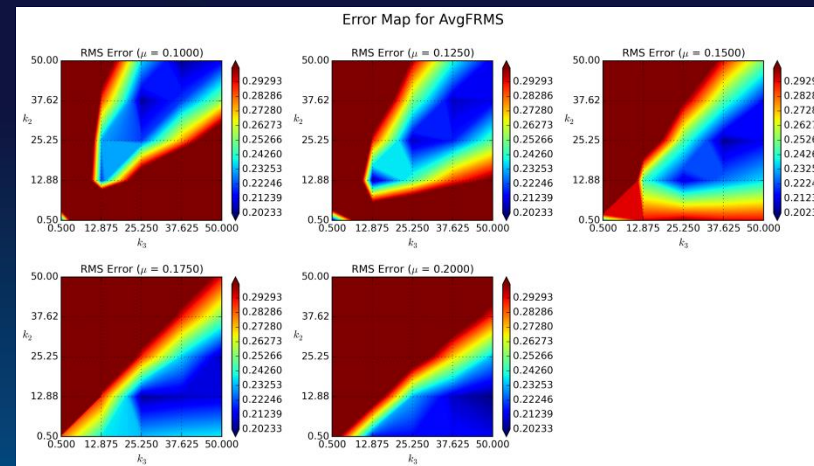
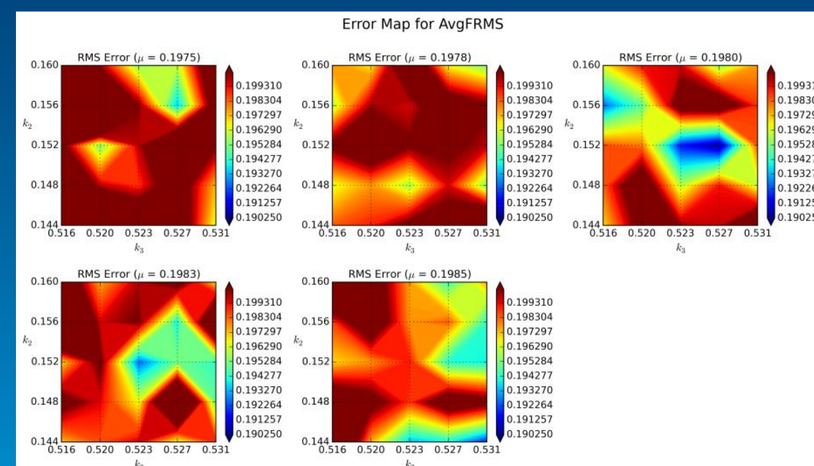
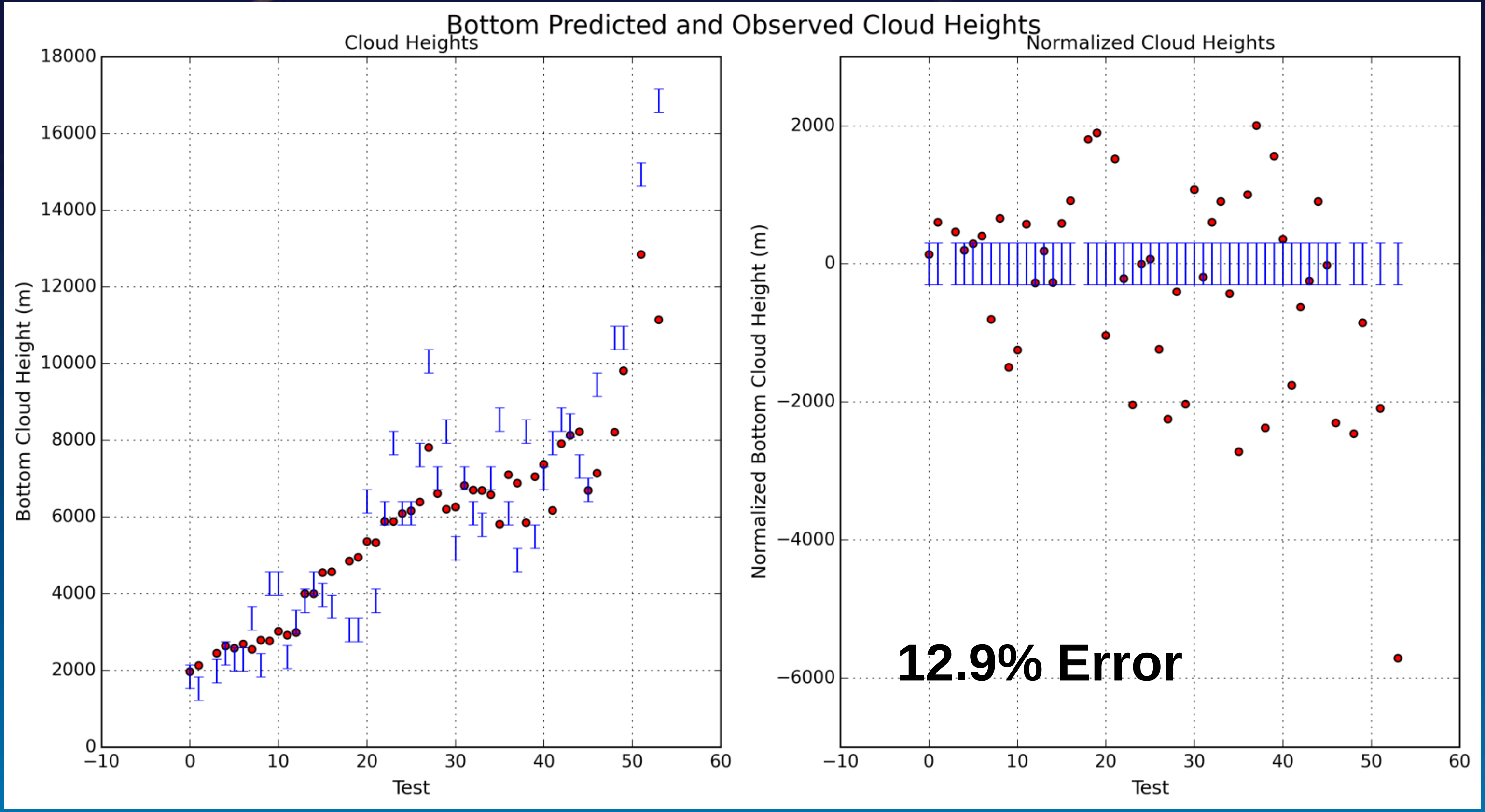
# Model Tuning & Validation

- **<u>Iterative methodology</u>**
  - Each local FRMS error minima is used to start a new iterative search branch
  - Each iteration uses a 5 x 5 x 5 parameter grid
  - The parameter space bounds are reduced by 50% in each direction, centered about the local minima, for each new iteration
  - The iteration completes when the local FRMS minima between two subsequent iterations converge within 1%
- **<u>Color contour maps</u>**
  - Upper right – Initial step for iterative search
  - Lower right – Final step for iterative search
- **<u>Error minimizing tuning parameters</u>**
  - $\mu$ = 0.198, $k_2$ = 0.152, and $k_3$ = 0.52725



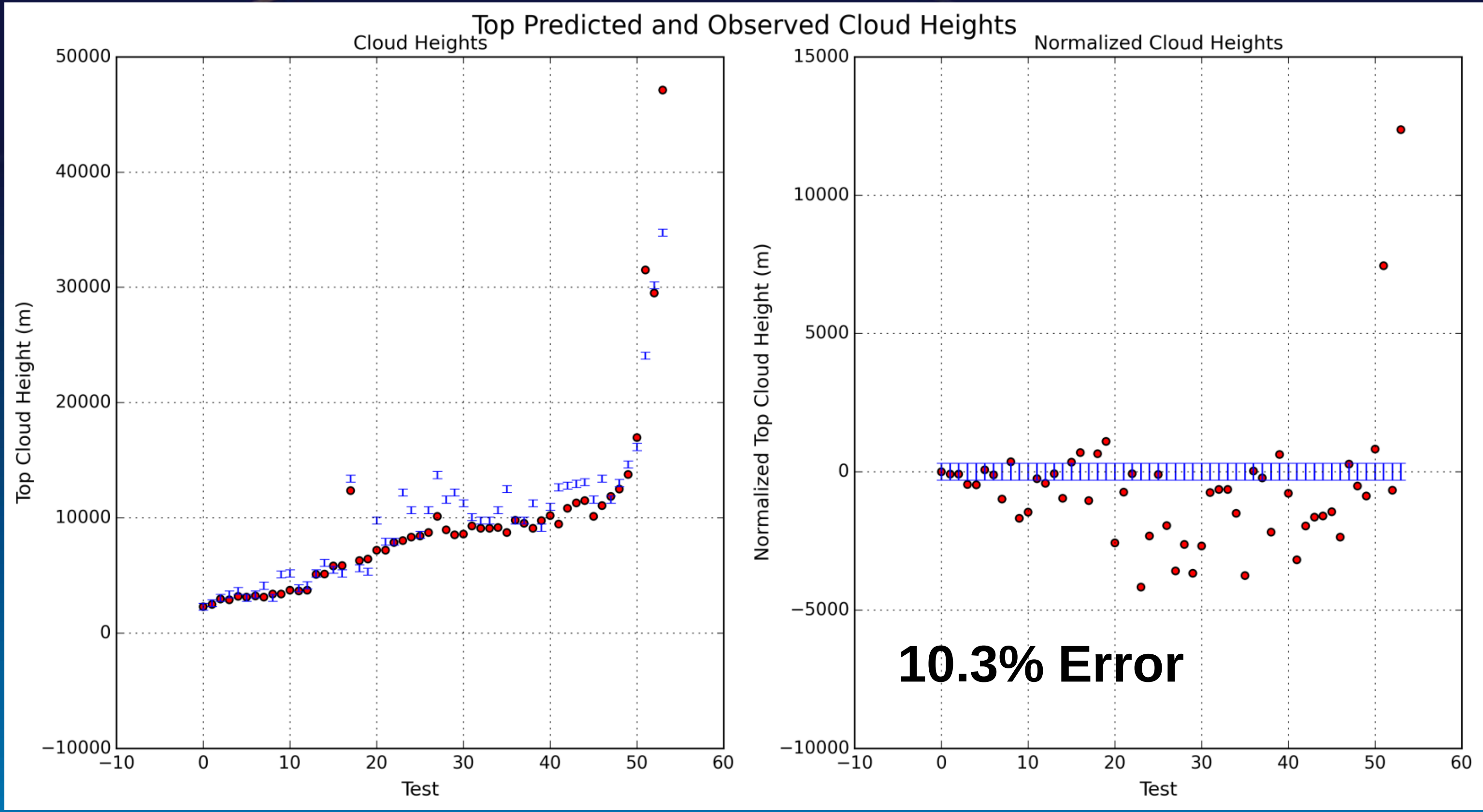



# Model Validation – Bottom Height




Predicted vs. Observed Cloud Bottom Heights across all 54 test cases using the best fit tuning parameters. (**Right**) Absolute cloud heights and (**Left**) Normalized cloud heights showing only differences.

# Model Validation – Top Height




Predicted vs. Observed Cloud Top Heights across all 54 test cases using the best fit tuning parameters. (**Right**) Absolute cloud heights and (**Left**) Normalized cloud heights showing only differences.

# DIORAMA Integration & Limitations

- **The cloud lofting module is fully integrated into DIORAMA**
  – Part of the LANL environment package
  – Couples with the LANL XG (x-ray and gamma ray) packages
  – Can be turned on/off with an optional module parameter
- **Limitations**
  – The model only simulates the buoyant forces and neglects the ballistic force which becomes important above ~50 km
  – The model is fundamentally a continuum fluid model which will break down above ~200 km due to the rarefaction of the atmosphere
  – The model neglects electromagnetic effects which would become important for high-altitude bursts above ~85 km
  – Lack of observed cloud heights limits validating the model for high altitude bursts

# Conclusions

- **A parcel methodology was applied to develop the DIORAMA cloud lofting module**
  - Based on the DELFIC model; treats cloud as homogenous unit
  - Solves set of 8 ODEs for cloud properties
  - Outputs the time history of the cloud height, radius, and other parameters
- **The cloud lofting module was tuned with 54 test cases**
  - An iterative brute force search was carried out to find the best fit tuning parameters
  - The best fit parameters yielded average cloud height errors of **12.9**% and **10.3**% for the bottom and top, respectively.
- **Allows for more accurate modeling of the propagation of delayed gamma rays in DIORAMA**